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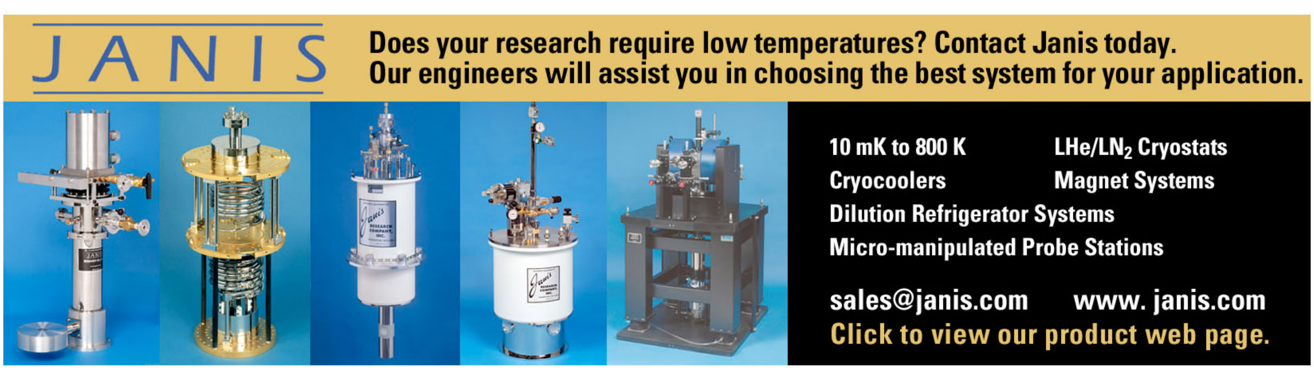

High voltage capacitor charge control by low voltage cycle counting

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We describe a low voltage open loop control for high voltage capacitor charging circuits. The control is achieved by counting the number of halfcycles from the line supply that are allowed to excite the HV transformer primary. This number of half cycles determines the amount of charge stored in the capacitor, therby setting its voltage to the desired value. This open loop system avoids the use of HV sampling or switching. An implementation is presented for a RC charging circuit, together with graphs and formulas for design purposes. LC resonant charging is also discussed.

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INTRODUCTION

In high voltage pulsers, the energy stored in the storage element (usually a capacitor or pulse forming network) is dissipated during the pulse, so that energy must be restored during the interpulse interval. A block diagram of a typical pulser circuit is shown in Fig. 1.

To the left of the storage element in Fig. 1 is what is called the charging circuit. Important requirements on the charging circuit are the following[1]:

a) the same amount of energy must be stored for every pulse;

b) the power supply must be isolated from the discharging circuit during the pulse time and for a short time after the pulse, providing adequate switch deionization.

The charging element can be an association of inductors, resistors and capacitors. With inductive charging two general types of circuits are normally used: resonant and nonresonant charging.[1] Both inductive and capacitive charging have the advantage of higher efficiency, against the well known maximum limit of 50% for resistor charging.

When control over the stored energy is desired, as in many laboratory applications, the following methods are generally used:

a) Variac control of input voltage to transformer primary;

b) sampling of the charging voltage in the storage element and switching off of the HV transformer when desired value is attained;

c) variable charging element (usually a potentiometer) and fixed pulse repetition rate;

d) variable pulse repetition rate with constant charging element.

These alternatives have some drawbacks, such as:

a) settling time which can be rather long and implementing servos to control the variac is expensive;

b) high voltage sampling is a problem in our case since adequate high voltage resistors are not generally available in Brazil;

c) need for high voltage variable components and lack of flexibility in pulse repetition rate.

Therefore, it would be convenient to have a fast HV control on the low voltage side, preferably an open loop system to avoid high voltage sampling.

In the system we have developed, a specific number of half cycles from the ac line are used to charge the capacitor via a full wave rectifier and a limiting resistor. The stored high voltage can thus be controlled in an open loop fashion by counting the number

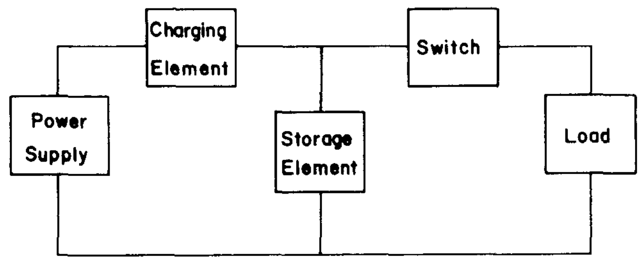

FIG. 1. Block diagram of typical pulser circuit.

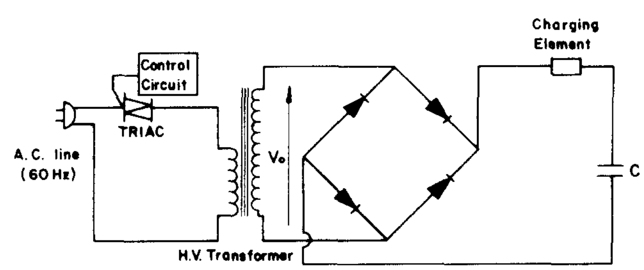

FIG. 2. Resistive charging circuit.

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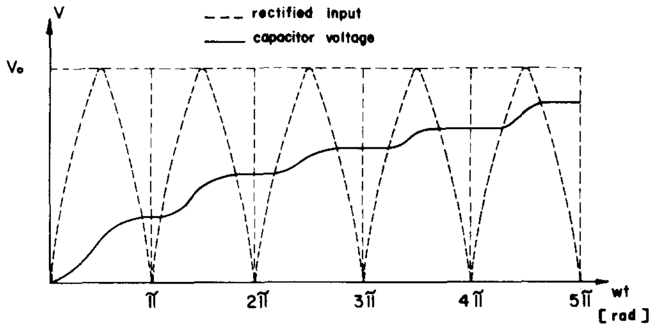


FIG. 3. Voltage input and voltage rise in the capacitor for the case of resistive charging.

of these half cycles. The control is achieved by means of an electronic switch such as a TRIAC as shown in Fig. 2 activated by a suitable control circuit. In our

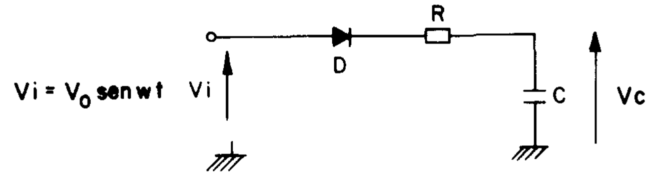


FIG. 4. Equivalent circuit for analysis of resistive charging.

case a convenient maximum repetition rate for the HV output pulse, is determined, as shown in the next section by the choice of RC and the line frequency of 60 Hz. The open loop system described avoids HV sampling or switching. Another interesting feature of this circuit is that during the discharge pulse, the charging circuit is disconnected, as the TRIAC is in its off state, ensuring protection against a short circuited load.

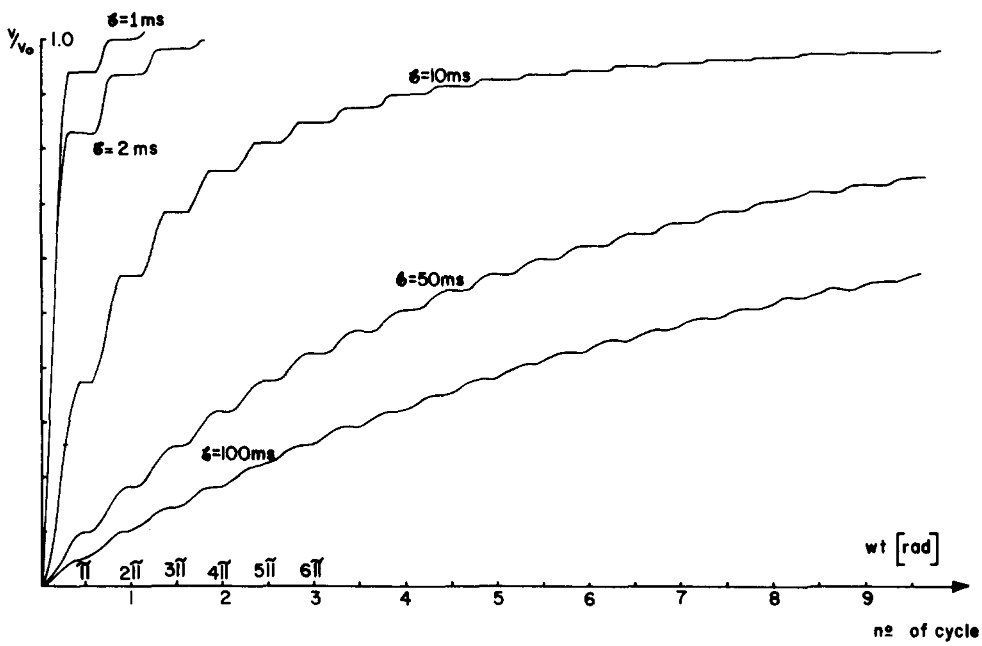


FIG. 5. Calculated capacitor voltage rise for different values of the time constant $\tau = RC$.

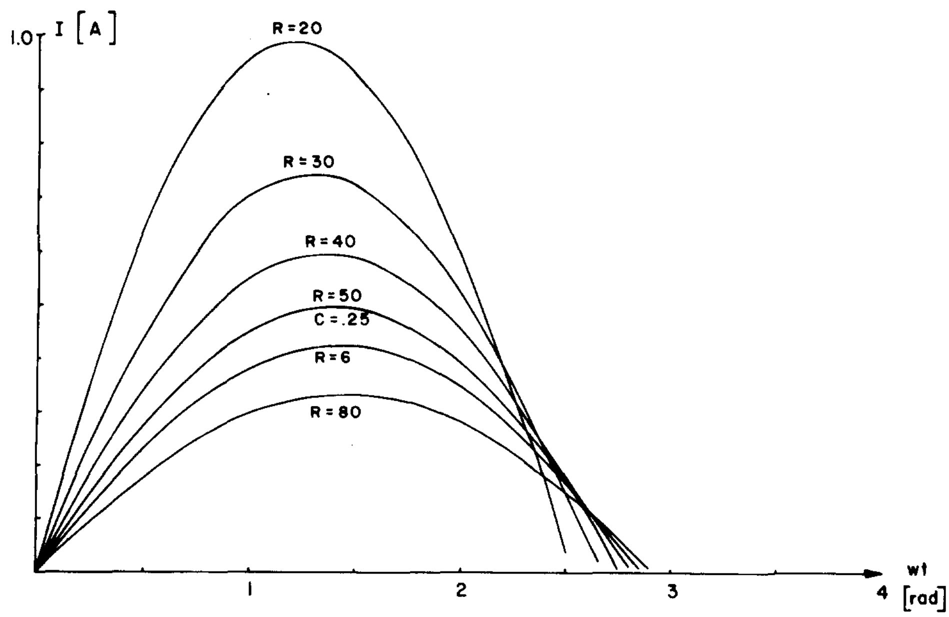


FIG. 6. First current pulse in resistive charging for $C = 0.25\ \mu F$ and different R values (in $k\Omega$). The input voltage in kilovolts is $V = 30 \sin\omega t$.

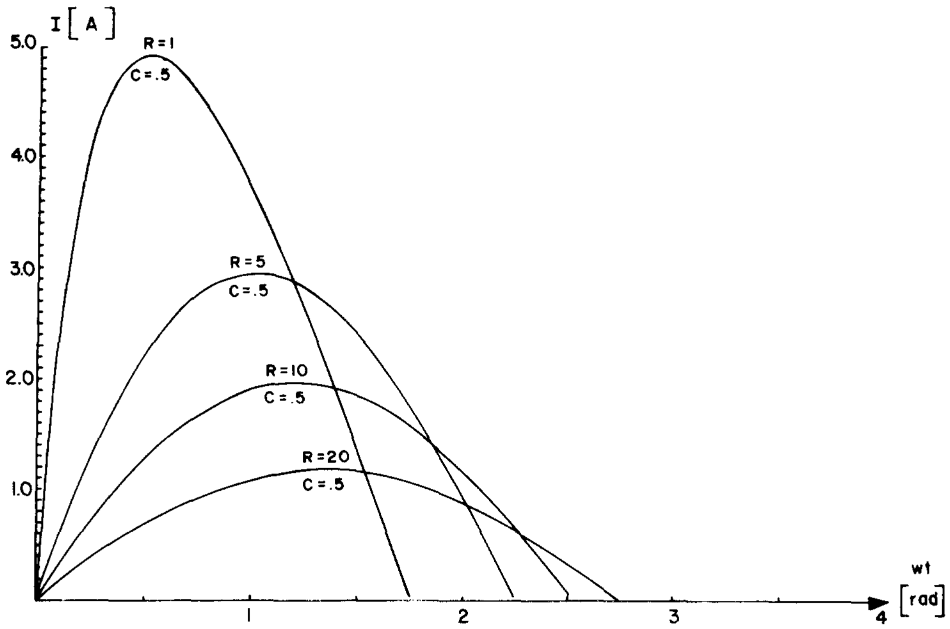


FIG. 7. Same conditions as Fig. 6 but with $c = 0.5\ \mu F$.

I. RC CHARGING CIRCUIT ANALYSIS

The corresponding circuit is represented in Fig. 2.

To minimize transients we shall determine that the phase of the ac input is zero when we switch on the TRIAC. The voltage waveform on the capacitor of Fig. 2 is a function of the number of half-cycles gated by the TRIAC as shown in Fig. 3. In the cycles subsequent to the first, the switching phase for the charging current will be different from zero due to the charge stored in the capacitor. This will set the initial conditions for each cycle. The equations governing the equivalent RC charging circuit of Fig. 4, are given by Eq. 1 below, where V_c is the capacitor stored voltage and V_0 is the peak input voltage.

Half-cycle no.

$$RC\,\frac{dVc}{dt} + v_c = v_0 \sin\omega t \qquad 1$$

$$RC\,\frac{dVc}{dt} + v_c = v_0 \sin(\omega t + \phi_2) \qquad 2$$

$$\vdots$$

$$RC\,\frac{dVc}{dt} + v_c = v_0 \sin(\omega t + \phi_n) \qquad n \qquad (1)$$

The initial condition for each half-cycle is given by the charge stored in C when the current $I_c(t) = C(dVc/dt)$ goes to zero in the preceding cycle. The phase ϕ_n is determined by that condition as: $\sin\phi_n = Q_{n-1}/V_0C$,

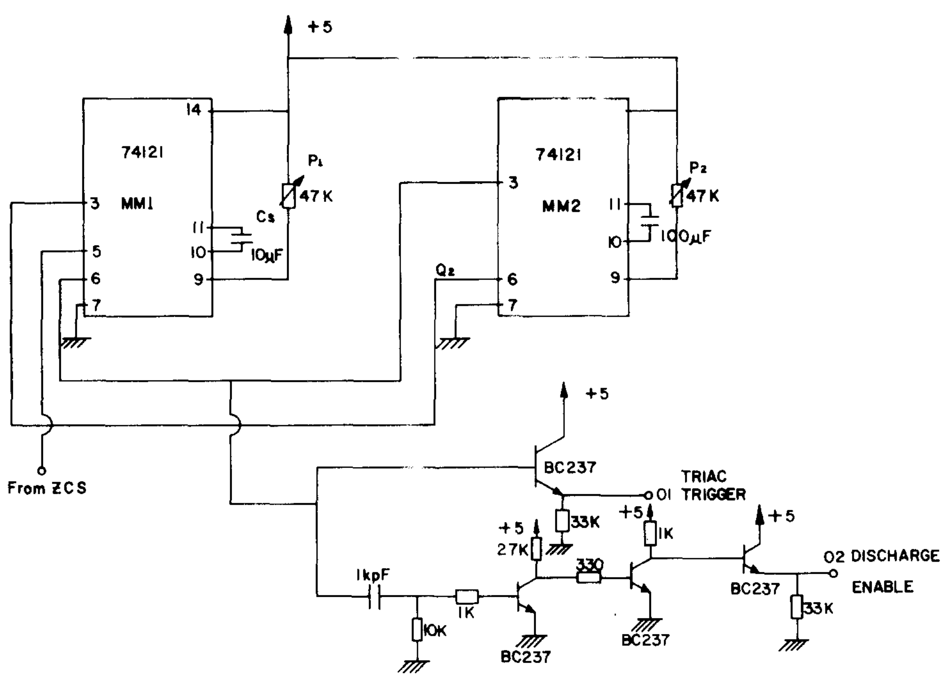
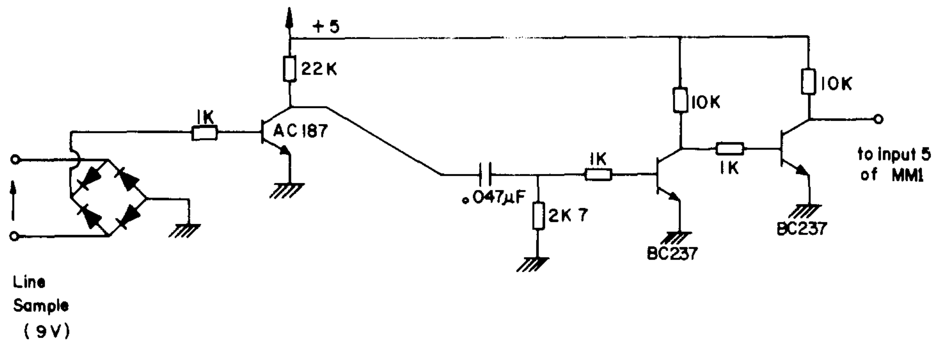


FIG. 8. Control circuit for resistive charging.

FIG. 9. Zero crossing switch circuit.



where Q_{n-1} is the capacitor charge at the end of cycle $(n-1)$.

The solution to these equations for each cycle is given by:

$$v_c(t) = \frac{v_0}{1+p^2}\left[(P^2 \sin\phi_n + P\cos\phi_n)\exp(-\omega t/P) + \sin(\omega t + \phi_n) - P\cos(\omega t + \phi_n)\right], \quad (2)$$

where the parameter P is ωRC and ϕ_n is determined by the stored charge in the capacitor at the end of the preceding cycle. The voltage rise given by Eq. 2 is illustrated in Fig. 5 for some values of the time constant RC. From Fig. 5 we see that:

a) increasing the RC time constant provides better voltage resolution

b) resolution increases towards the end of the charging period. This is the region of interest for HV control

c) decreasing the RC time constant allows a higher repetition rate.

Condition (a) and (c) are in conflict. Resolution increases when the maximum allowed repetition rate decreases, so that a compromise for the RC value exists. We feel that adequate time constants are around ten miliseconds for 60 Hz supply. From Fig. 5 we see that for $RC = 10$ ms and a resolution better than 7% at 10 pps the voltage can be controlled between $0.7\ V_0$ and $0.93\ V_0$. It may be interesting to note that the resolution can be increased if a higher frequency ac supply is available. For design purposes, the first current pulse shape (the highest) is plotted in Fig. 6 and Fig. 7 for certain values of R and C.

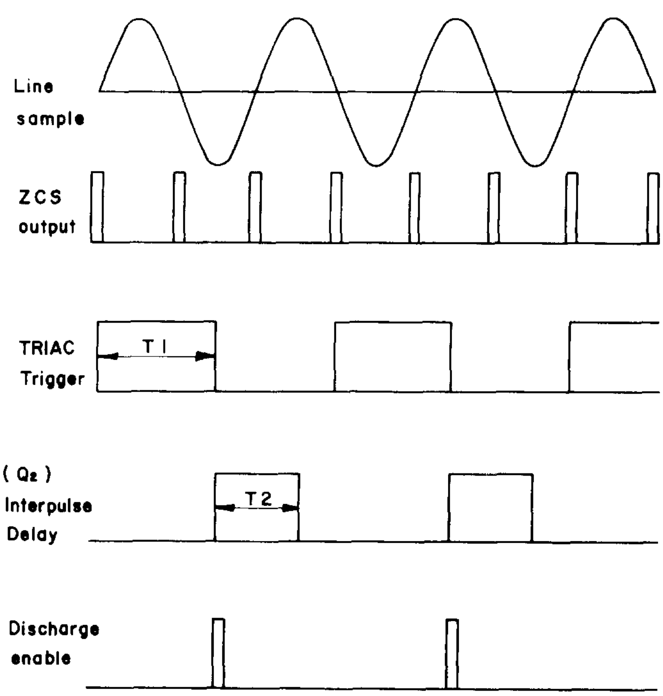


FIG. 10. Voltage waveforms in the control circuit for resistive charging.

II. CONTROL CIRCUIT SPECIFICATION

Requirements on the control circuit are:

a) it must be phase locked to the line supply so that switching on of the TRIAC always happens in zero phase, minimizing rf noise and ensuring repeatable charging voltage from pulse to pulse

b) it must supply *continuous* trigger gate current to the TRIAC during the specified time interval since the TRIAC current will be zero in the dead zones seen in Fig. 3

c) it must enable the discharge control circuit so that discharge will occur only after charging is completed.

The circuit in Fig. 8 can be used for this purpose. The monostable multivibrator MM1 provides the TRIAC trigger pulse, with duration controlled by potentiometer P1.

MM1 is triggered by the zero crossing switch of Fig. 9 and is enabled by MM2, which provides the interpulse delay. This ensures condition *a* of this section. When the TRIAC trigger pulse ends, a synchronism pulse is produced in output 02, enabling the discharge control circuit. The sequence of events can be understood from

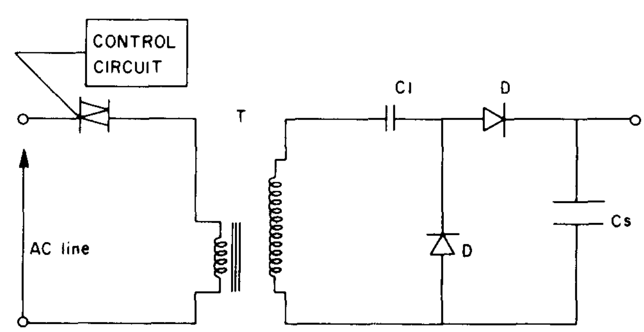


FIG. 11. Capacitive limited charging circuit. C_1 is the limiting capacitor and is usually smaller than Cs, the storage one.

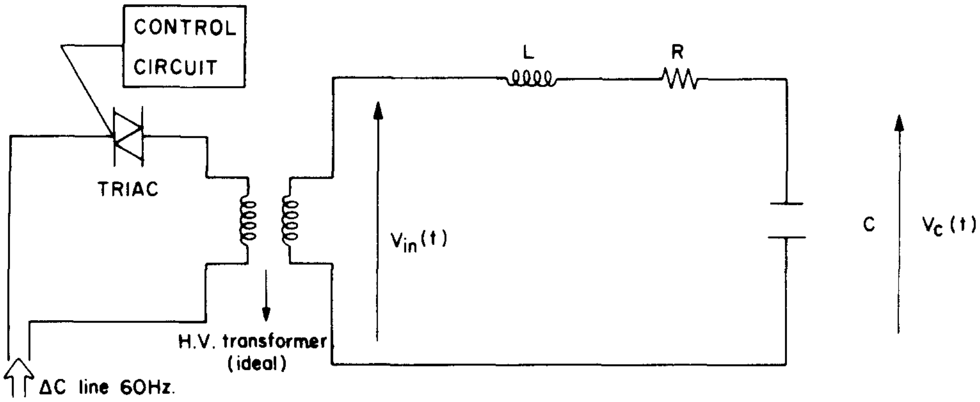


FIG. 12. *LC* charging circuit with TRIAC control.

the diagrams of Fig. 10. The described circuit has been used for charging a two stage Marx generator used in TEA laser excitation. The Marx bank was composed of two 0.5 μF/50 kV fast discharging capacitors, each charged through a 20 kΩ resistor. Repetition rates up to 10 Hz at 90% full charge could be obtained, with a resolution better than 5%. Of course, efficiency is low (<50%) but higher efficiencies can be attained using a small capacitor instead of the resistor, as the current limiting element in a voltage doubler configuration (Fig. 11). With this modification our calculated efficiency was 97%.[2]

III. LC RESONANT CHARGING

In this case the charging element is an inductance L such that the resonance condition is fullfilled; $\omega^2 LC = 1$, where ω is the angular frequency of the input signal to the network of Fig. 12. Resistor R accounts for the losses in the circuit and is usually kept as small as possible.

In the case of low losses, that is high quality factor Q, with input voltage $V_{in}(t) = V_0 \cos(\omega t + \phi)$ the voltage stored in the capacitor is given after n half cycles by[1]:

$$V_c(n\pi) = \pm \frac{n\pi}{2} V_0 \sin\phi \tag{3}$$

as long as $Q = 1/\omega RC \gg n\pi/2$. The plus and minus sign apply respectively for n even or odd.

In contrast to the case of resistive charging, the stored charge increases linearly with the number of cycles allowed to excite the network. Another interesting feature is the possibility of voltage multiplication. Of course one must choose n even *or* odd, according to the desired polarity, and be careful about the Q limitation. This condition limits be maximum storage capacitance since the expression above can be rewritten: $C \ll 2/n\pi\omega R$.

The phase ϕ of the input voltage must also be chosen carefully because from Eq. 3 we see that lower values of $\sin\phi$ increase resolution by reducing the voltage multiplication factor. The efficiency of the circuit is also degraded with decreasing $\sin\phi$: maximum efficiency is obtained with ϕ near $\pi/2$ and is given by: (1)

$$e = 1 - \frac{n\pi}{3Q}. \tag{4}$$

In Fig. 11 we show how the TRIAC control can be applied to resonant charging, in complete analogy to the resistive charging circuit.

[1] G. N. Glasoe and J. V. Lebacqz, *Pulse Generators* (Dover, New York, 1965), ch. 9.
[2] D. M. Soares and C. H. Brito Cruz, 31st Meeting of the Brazilian Society for Advancement of Science—Cienc. e Cult. (São Paulo) Supl. **31**(7), 222 1979—July, 7–14, 1979, Fortaleza, Brazil.